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Highlights of the VERITAS Blazar Observation Program

WYSTAN BENBOW[1] FOR THE VERITAS COLLABORATION[2]
[1] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-20, Cambridge, MA, 02180, USA*
[2] *see J. Holder et al. (these proceedings) or http://veritas.sao.arizona.edu/conferences/authors?icrc2011*
wbenbow@cfa.harvard.edu

Abstract: The VERITAS array of 12-m atmospheric-Cherenkov telescopes in southern Arizona began full-scale operations in 2007, and it is one of the world's most sensitive detectors of astrophysical VHE ($E >$100 GeV) γ-rays. Forty-one blazars are known to emit VHE photons, and observations of blazars are one of the VERITAS Collaboration's Key Science Projects (KSPs). More than 400 hours per year are devoted to this program, and $\sim$100 blazars have already been observed with the array, in most cases with the deepest-ever VHE exposure. These observations have resulted in 20 detections, including 10 new VHE blazars. Highlights of the VERITAS blazar observation program, and the collaboration's long-term blazar observation strategy, are presented.

Keywords: VERITAS, AGN, Blazar, Gamma-ray, TeV, VHE

1 Introduction

For almost two decades, the study of blazars has been a major component of the scientific program of VHE γ-ray observatories. Forty-one blazars, a class of AGN with relativistic jets pointed along the line of sight to the observer, are observed to emit VHE γ-rays. The VHE blazar population includes four blazar subclasses: 30 high-frequency-peaked BL Lac objects (HBLs), 5 intermediate-frequency-peaked BL Lac objects (IBLs), 3 low-frequency-peaked BL Lac objects (LBLs), and 3 flat-spectrum radio quasars (FSRQs). The redshifts of the known VHE blazars range from $z = 0.030$ to at least $z = 0.536$, and the photon spectra of the observed VHE emission is often soft ($\Gamma_{obs} \sim 2.5-4.6$). However, it is important to note that this is largely due to the softening of the emitted blazar spectra by the attenuation of VHE photons on the extragalactic background light (EBL). Approximately 60% of the known HBLs exhibit some variability, and most of the non-HBL blazars are detected at VHE only during flaring episodes. Although VHE flux variability is commonly observed[1], rapid (minute-scale), large-scale (factor of 100) variations of the VHE flux are relatively rare (see, e.g., [2]). Only four VHE blazars have ever been observed at more than the Crab Nebula flux (1 Crab), and of these, only Mkn 421 and Mkn 501 have been seen in multiple >1 Crab flaring episodes.

Understanding VHE blazars and their related science relies on expanding the known population, and making precision measurements of their spectra (particularly at the highest energies) and their variability patterns (e.g., timescales, flux range, and spectral changes). Contemporaneous multiwavelength (MWL) observations are a key component of these studies since these highly-variable sources emit over the entire broadband spectrum. These MWL studies enable modeling of the blazars' double-humped spectral energy distributions (SEDs), as well as searches for correlations in the flux/spectral changes observed that may indicate commonalities in the origin of the observed emission.

2 The VERITAS Blazar KSP

VERITAS began routine scientific observations with the full array in September 2007. The performance metrics of VERITAS [1] include an energy resolution of $\sim$15%, an angular resolution of $\sim$0.1°, and a sensitivity yielding a 5 standard deviation (σ) detection of an object with flux equal to 1% Crab in $\sim$25 hours. VERITAS observations are performed for $\sim$1100 h each year, and from 2007-10, observations of blazars averaged $\sim$410 h per year. Table 1 shows the 20 VHE blazars (15 HBL and all 5 known VHE IBL) detected by VERITAS, which include 10 discoveries. The VERITAS blazar KSP consists of:

i. A discovery program: Several blazars are selected annually for VERITAS observations with the goal of increasing the VHE blazar population, particularly in the non-HBL subclasses and at higher redshifts. Through these efforts, and those of other VHE observatories, the VHE blazar catalog is rapidly expanding. This is well illustrated by the sky map in Figure 1, which shows 3 VHE blazars (2 IBLs and 1 HBL) all contained within the VERITAS field of view (3.5°). Highlights from the discovery program are presented elsewhere in these proceedings [6].

1. Typically variations of a factor of 2-3 are seen on timescales ranging from days to years.

Blazar	z	Type	$\log_{10}(\nu_{\rm synch})$
Mrk 421	0.030	HBL	18.5
Mrk 501	0.034	HBL	16.8
1ES 2344+514	0.044	HBL$^{\beta}$	16.4
1ES 1959+650	0.047	HBL	18.0
W Comae†	0.102	IBL	14.8
RGB J0710+591†	0.125	HBL	21.1
H 1426+428	0.129	HBL	18.6
1ES 0806+524†	0.138	HBL	16.6
1ES 0229+200	0.140	HBL	19.5
1ES 1440+122†	0.162	IBL	16.5
RX J0648.7+1516†	0.179	HBL*	-
1ES 1218+304	0.184	HBL	19.1
RBS 0413†	0.190	HBL	17.0
1ES 0414+009	0.287	HBL	20.7
PG 1553+113	$0.43 < z < 0.50$	HBL$^{\beta}$	16.5
3C 66A†	?	IBL	15.6
B2 1215+30	?	IBL	15.6
PKS 1424+240†	?	IBL	15.7
1ES 0502+675†	?	HBL	19.2
RGB J0521.8+2112†	?	HBL*	-

Table 1: The 20 blazars detected at VHE with VERITAS. The 10 VHE discoveries are marked with †. The catalog redshifts for B2 1215+30 (0.130), 1ES 0502+675 (0.341) and 3C 66A (0.444) are considered uncertain, and the redshift range for PG 1553+113 is quoted at the lower and upper limits determined by [3] and [4], respectively. The classifications and synchrotron peak frequencies are taken from [5], except for four cases: two (marked with asterisks) where the classification is determined from VERITAS-led MWL studies, and two (marked with β) where the historical HBL classification is used.

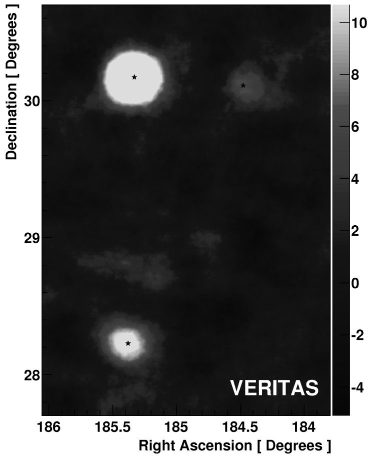

Figure 1: The significance map for a single field of view containing three VHE blazars (1ES 1218+304, W Comae & B2 1215+30). All three sources are point-like, but appear to have a different size due to the saturation on the color scale. The total exposure for this map is ∼130 h of observations, but the effective exposure at each blazar position varies considerably because the three sources were initially observed individually.

ii. A target-of-opportunity (ToO) observation program: Blazar observations can be triggered by either a VHE discovery or a flaring alert from various optical, X-ray, MeV-GeV (Fermi-LAT), and TeV blazar monitoring programs.

iii. A MWL observation program: Contemporaneous MWL observations are organized for most of the known VHE blazars regularly observed by VERITAS. In addition, ToO observation proposals for MWL measurements are also submitted to lower-energy observatories, and are triggered by a VERITAS discovery or flaring alert.

iv. An EBL/IGMF program: Studies of distant VHE candidates, and deep exposures on known hard-spectrum VHE blazars, are performed to constrain, and possibly measure, the EBL and the intergalactic magnetic field (IGMF).

From 2007-10, ∼80% of the VERITAS blazar data came from discovery observations and follow-up observations of any new sources. In September 2010, the emphasis of the Blazar KSP changed to aim for a 40:60 ratio between discovery observations and exposures of known VHE sources.

3 Highlights for Known VHE Blazars

Mrk 421 is the longest-known VHE blazar, and generally has the brightest VHE flux. It is easily the best-studied HBL at VHE, and VERITAS has acquired nearly 80 h on this blazar since 2007, largely during flaring states identified with the Whipple 10-m telescope. A total of 47 hrs of VERITAS and 96 hrs of Whipple 10m data taken between 2006 and 2008 are presented in [7]. During this campaign, bright VHE flares reaching flux levels of ∼10 Crab are detected, and the VHE data are complemented with radio, optical, and X-ray (RXTE and Swift) observations. Flux variability is found in all bands except for the radio waveband. Interestingly, the VHE and X-ray flux are often correlated, with both bands showing spectral hardening with increased flux levels. For 18 nights during a 118-day campaign in 2008, it was possible to generate contemporaneous SEDs, each of which can be described by a one-zone synchrotron-self-Compton (SSC) model. VERITAS monitoring of the VHE flux from Mrk 421 in 2009-10 reveals an elevated state during the entire season. In particular, an extreme flare was observed for nearly 5 h live time on February 17, 2010, during which the VHE flux averaged ∼8 Crab and showed variations on timescales of approximately 5-10 minutes [8]. Results from the extensive MWL observations during the 2009-10 season, including ∼20 h of VERITAS data, are in preparation. During the 2010-11 season, strong variations of the VHE flux from Mrk 421 were observed, although, the flux never exceeded 1 Crab.

Mrk 501 is perhaps the best-studied VHE blazar after Mrk 421. Its VHE emission is relatively bright, and it has a long history of extreme outbursts and spectral variability. The VERITAS collaboration has performed several MWL observation campaigns on this HBL: during low states in May-June 2008 [9] and March 2009 [10], and during/after a VHE flare initially detected by the Whipple 10-m [11] in late-April 2009 [12]. The low-state SED measured dur-

ing the March 2009 campaign (including Suzaku, Fermi-LAT, MAGIC and VERITAS data), contrasts remarkably with the SED from an extreme outburst observed on April 16, 1997. Here the energy of the X-ray peak differs by over two orders of magnitude between the two states, while the VHE peak location varies little, likely due to the onset of Klein-Nishina effects. Regardless of this, a simple SSC scenario can successfully model both states with the primary difference being the injected electron spectra. The entire 2009 VERITAS data set is presented in [12] as part of an unprecedented campaign with instruments including Fermi-LAT, MAGIC, Swift, VLBA, RXTE, F-GAMMA, GASP-WEBT, and other smaller observatories. The measured SED is the most detailed ever, and is again well described by a standard one-zone SSC model. In 2011, strong variations of the VHE flux from Mrk 501 were observed, but the VHE flux never exceeded 1.5 Crab.

1ES 2344+514 is the third blazar detected at VHE, and this HBL was observed by VERITAS for 18.1 h quality-selected live time as part of an intense MWL observation campaign from October 2007 to January 2008. The VERITAS observations yield a strong (20σ) detection of a variable VHE flux [13]. On December 7, 2007, a strong VHE flare of 48% Crab above 300 GeV was observed by VERITAS. Excluding this flare, the measured VHE flux is still variable and averages 7.6% Crab. The VHE spectrum on the night of the flare ($\Gamma = 2.43 \pm 0.22$) is harder, but does not differ significantly from that determined with VERITAS from the rest of the data ($\Gamma = 2.78 \pm 0.09$). Both the VHE flux and the X-ray flux (Swift & RXTE) vary by a factor of $\sim$7 during the campaign, and significant correlations between the two bands are found. A one-zone SSC model can describe the SEDs determined both during the flare and in the lower-flux state. VERITAS monitoring of the VHE flux from 1ES 2344+514 in 2010 yielded the lowest value ($\sim$2% Crab) ever recorded from this object.

1ES 1959+650, a well-studied HBL, was observed by VERITAS for 5.3 h of quality-selected live time in 2007-09. Analysis of these data yields an excess of $\sim$150 γ-rays (12.3σ), corresponding to a flux of $\sim$18% Crab. The observed flux and photon spectrum are consistent with those measured during previous low-emission states of this source. A MWL observation campaign on 1ES 1959+650, with VERITAS, Fermi-LAT and RXTE, is planned in 2011.

H 1426+428 was first detected during an outburst in 2001 [14]. This HBL was observed by VERITAS for $\sim$22 h quality-selected live time between 2007 and 2011. A weak excess, 5.2σ, is observed in these data, marking the first time H 1426+428 is detected since 2002. The observed flux is <2% Crab, well below the value (13% Crab) reported during its VHE discovery, and also below any other published VHE flux or limit from this source.

1ES 1218+304 is an HBL with a VHE spectrum that is unusually hard considering its redshift and the effect of the EBL. VERITAS first detected this blazar during 17.4 h of commissioning-phase observations in January - March 2007 [15]. The $\sim$10σ detection corresponds to an observed flux of $\sim$6% Crab above 200 GeV, and the resulting spectrum between 160 GeV and 1.8 TeV is well described by a power-law function with photon index $\Gamma = 3.08 \pm 0.34$. In 2008-09, VERITAS monitored the flux from 1ES 1218+304 for $\sim$27 h good-quality live time. The blazar is strongly detected ($\sim$22σ), and clear day-scale variations of the VHE flux are seen [16]. Although the VHE flux varied by factor of $\sim$4, reaching $\sim$20% Crab, the VHE spectrum did not change significantly during the campaign ($\Gamma_{avg} = 3.07 \pm 0.09$). The relative hardness of the 1ES 1218+304 spectrum can be used to derive limits on the EBL very close to the best. However, the derived EBL constraints can be weakened by invoking kpc-scale jet-emission scenarios for this and other distant, hard-spectrum VHE blazars. Fortunately, the observed day-scale variability rules these models out [16]. During VERITAS monitoring of 1ES 1218+304 in 2011, the blazar is strongly detected in a season-long elevated flux state ($\sim$12% Crab).

PG 1553+113 is a hard-spectrum ($\Gamma_{LAT} \sim 1.66$) Fermi-LAT blazar [17]. It is likely the most distant HBL detected at VHE (see $z > 0.43$ from [3]). It was observed by VERITAS for $\sim$60 h of quality-selected live time between May 2010 and May 2011. These data result in the most significant VHE detection (39σ) of this HBL. The time-averaged VHE flux is 10% Crab above 200 GeV, higher than the archival VHE measurements, and the photon spectrum is well described between 175 GeV and 500 GeV by a power-law function with photon index $\Gamma = 4.41 \pm 0.14$. The VHE spectrum can be used to set an upper limit on the redshift of $z < 0.5$. More details regarding the VERITAS detection of PG 1553+113 can be found in these proceedings [4].

1ES 0229+200 is one of the hardest-spectrum VHE blazars known ($\Gamma_{HESS} \sim 2.5$; [18]). It was observed by VERITAS as part of an intense MWL observation campaign for $\sim$46 h live time from 2009-11. A strong signal is detected ($\sim$600 γ-rays, 9.0σ) in these observations corresponding to an average VHE flux of $\sim$2% Crab above 300 GeV. The VERITAS flux is variable on a timescale of months, and the preliminary VHE spectrum measured between $\sim$220 GeV and $\sim$15 TeV has photon index $\Gamma = 2.44 \pm 0.11$. The results of the MWL campaign are in preparation. It is interesting to note that 1ES 0229+200 is the only VERITAS-detected blazar not included in the 1FGL catalog [17].

1ES 0414+009 1ES 0414+009 is the most distant VHE HBL with a well-measured redshift ($z = 0.287$). It was observed by VERITAS for $\sim$55 h of quality-selected live time from January 2008 to February 2011. An excess of VHE γ-rays is detected ($\sim$7σ) from this Fermi-LAT source ($\Gamma_{LAT} \sim 1.94$; [17]). The observed VERITAS spectrum between $\sim$230 GeV and $\sim$1.8 TeV is relatively hard ($\Gamma = 3.4 \pm 0.5$) considering EBL-related effects, and consistent with that observed during the HESS discovery [19]. The observed VERITAS flux is somewhat higher ($\sim$1.6% Crab) than measured by HESS (0.6% Crab above 200 GeV), although the large data-sets used by both experiments are not simultaneous. Results from a contemporaneous MWL observation campaign are in preparation.

B2 1215+30, an IBL discovered at VHE during a flare in January 2011[20], was observed[2] for ~55 h of quality-selected live time between December 2008 and April 2011. The measured excess of ~240 γ-rays (6.3σ) corresponds to a VHE flux of ~1% Crab. There is a weak indication that the flux observed by VERITAS in 2011 may be higher than seen from 2008-10. The VERITAS flux is consistent with that (2 ± 1% Crab) reported during the MAGIC discovery.

4 The Long-term Blazar Strategy

In 2010, a plan for the future of the VERITAS blazar KSP was developed. Using the average annual blazar exposure, ~410 h per year, as the baseline, an observation program was created that focused on intensive observations of known sources, while maintaining an active discovery effort. The major components of this program include:

i. Long-term Monitoring (210 h / yr): VERITAS will regularly monitor 14 selected VHE blazars (~70% of northern VHE BL Lac population) during each season to maximize the chance of detecting any VHE flaring episodes while simultaneously building deep exposures (~100 to ~200 h total). The selected targets consist of five EBL/IGMF-relevant HBLs (i.e., distant, hard-spectrum sources), four nearby, bright HBL where extreme flares are perhaps most likely, and five non-HBL blazars for studies to unravel the mechanisms behind the blazar sequence. Table 2 shows the blazars monitored and their existing VERITAS exposure. Contemporaneous radio, optical/UV, X-ray and GeV monitoring will be organized to enable source modeling, and ToO observation proposals in the optical-to-X-ray waveband will be submitted annually to ensure coverage of important flaring events.

ii. Discovery Program (~100 h / yr): A Fermi-LAT-guided discovery effort will be continued, but the focus will move towards higher-risk/higher-reward endeavors, and will be split between non-HBL targets (to expand the understanding of the blazar sequence), and high-redshift candidates (useful for EBL/IGMF studies). In addition, observations of previously-viewed candidates showing a marginal excess in existing VERITAS data will continue.

iii. ToO Program (~100 h / yr): This is used to respond to flares from the monitoring program, to deepen exposures on new discoveries, and to respond to high-value discovery opportunities (e.g., FSRQs) indicated by flaring at lower energy. To aid this effort, optical, and often X-ray monitoring, of all known VHE blazars and high-value candidates is set up, in addition to automatic LAT analysis pipelines[21].

5 Conclusion

Blazar observations are a major component (~40%) of the scientific program of VERITAS. Twenty VHE blazars are detected with the observatory, including 10 VHE discoveries. The VERITAS studies of these emitters are largely the most sensitive ever, and have yielded a number of interesting results. A long-term plan for the VERITAS blazar KSP is organized, and it includes both a robust discovery effort, and a program to produce unprecedented VHE data sets, in terms of sensitivity, duration and MWL coverage, for most of the northern blazar population. Clearly, there are many exciting VERITAS blazar results still to come.

VHE Blazar	Primary Study	Exp. [h]
1ES 0229+200	EBL/IGMF	51
1ES 0414+009	EBL/IGMF	55
RGB J0710+591	EBL/IGMF	46
1ES 1218+304	EBL/IGMF	81
PG 1553+113	EBL/IGMF	65
Mrk 421	Bright HBL	78
Mrk 501	Bright HBL	26
1ES 1959+650	Bright HBL	5
1ES 2344+514	Bright HBL	24
3C 66A	IBL	44
W Comae	IBL	63
PKS 1424+240	IBL	45
S5 0716+714	LBL	13
BL Lac	LBL	13

Table 2: The 14 blazars selected for long-term monitoring with VERITAS, and their existing good-quality VERITAS exposure (as of May 31, 2011). The exposure goal for each target, which may be exceeded or revised, ranges from 5 h to 25 h per year.

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2. Almost all of these data were taken as 0.5° wobbles on another VHE blazar, 1ES 1218+304, ~0.9° distant, resulting in a lower average sensitivity for the VERITAS exposure.